Buoyant Outflows in the Presence of Complex Topography

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LONG-TERM GOALS

The overarching goal is to elucidate the complex dynamics of outflows connecting basins through straits. The long term scientific goals are to (a) understand the physical mechanisms that control the exchange between two marginal seas with substantially different water mass characteristics (Aegean Sea and Black Sea) through a complex system of straits (Turkish Straits System); (b) quantify the pathways of the buoyant outflow and evaluate the influence on the dynamics of the receiving coastal areas, as well as on the Mediterranean Sea at large. The long term operational goal is to develop a high resolution numerical model of the Northern Aegean Sea, an island archipelago with intensely complex topography, nested within a coarser Mediterranean Sea model and coupled to a high resolution, unstructured grid model of the Turkish Straits system, which in itself will be coupled to a Black Sea model. The overall study goals are closely linked to several ancillary projects.

OBJECTIVES

The main *scientific objectives* are to:

a) provide new insights in the understanding of plume dynamics, analyzing the development of a plume that is generated by a buoyant outflow through a narrow strait (Dardanelles) and its evolution through a topographically complex marginal sea;

b) examine the relative role of buoyancy, wind stress and topography in determining the seasonal and inter-annual variability in the development and evolution of the Dardanelles plume;

c) quantify the transport rates and pathways of the low-salinity waters of Black Sea origin that enter the Aegean Sea (and hence the Mediterranean) through the Dardanelles Strait;

d) study the influence of the flow exchange through the Dardanelles Strait on the Aegean Sea coastal flows, cross-shelf exchanges and basin-wide eddy field;

e) examine if the inter-annual variability of the Dardanelles plume (in the context of changing outflow properties and regional atmospheric forcing) is related to changes in the export of dense waters from the Northern Aegean to the Eastern Mediterranean Sea.

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The main *operational objectives* are to:

f) explore a novel approach in ocean modeling, by developing techniques to parameterize flow exchange through narrow straits that cannot be properly resolved in ocean models;

g) enhance the predictive capability of operational Navy models, by developing and testing a methodology to link the Mediterranean and Black Sea basins that are currently uncoupled in all available global and regional Ocean General Circulation Models;

h) help optimize Navy missions in strategic areas of complex topography;

i) contribute to a prediction tool that is essential for optimizing Navy missions, especially near watersheds and strategic straits.

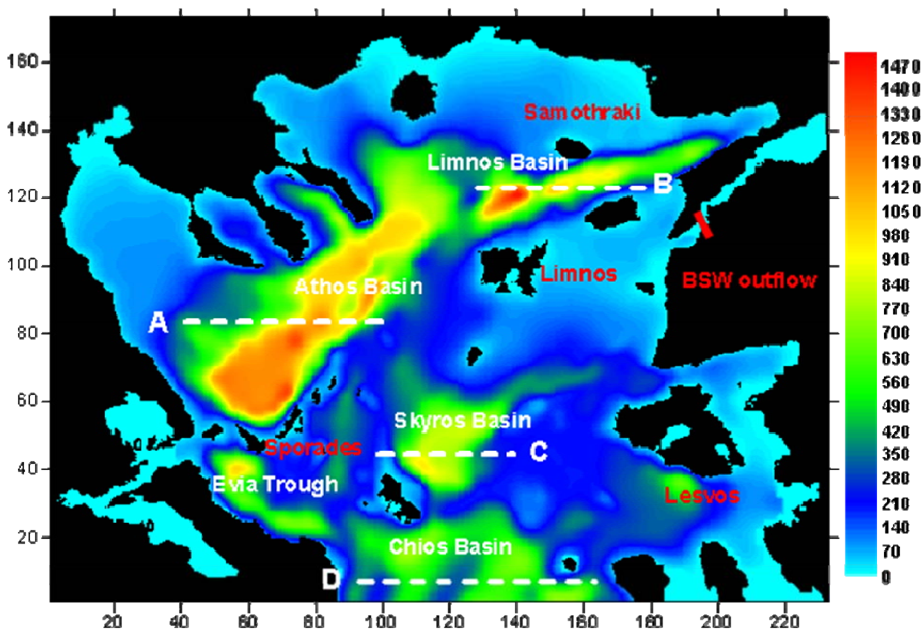

Fig. 1: The North Aegean Sea HYCOM model domain and bathymetry; certain major islands are marked. White dashed lines mark transects acroos the deepest basins employed in the results (A: Athos; B: Limnos; C: Skyros; D: Chios). The red line marks the boundary of the Dardanelles Strait "notch" where the BSW outflow is imposed.

APPROACH

A high resolution (1/50 degree, ~1.8 km) numerical model has been applied on the Northern Aegean Sea (NAS). The model domain extends from 22.5°E to 27°E and from 39°N to 41°N (Fig. 1); 20 hybrid layers are employed in the vertical. The bathymetry is derived from the NOAA General Bathymetric Charts of the Oceans (GEBCO, http://www.ngdc.noaa.gov/mgg/gebco/grid/1mingrid.html) 1 min bathymetry. In addition, extensive corrections for island passages and straits have been added, merging with local bathymetric data sets. Minimum depth is 2.4m and the deep areas reach 1500m. The model is based on the Hybrid Coordinate Ocean Model (HYCOM; http://hycom.rsmas.miami.edu), to take advantage of the flexible isopycnal-sigma-zlevel coordinate system and advanced mixing schemes, both important factors for the successful simulation of plume dynamics in areas of strong shallow to

deep topography transitions, as in the study domain. Boundary conditions have been provided through collaboration with NRL-SSC (A. Wallcraft and B. Kara); a regional Mediterranean Sea HYCOM model (resolution 1/25 degree) has been developed and has been running operationally since 2003 with the Navy Coupled Ocean Data Assimilation (NCODA; Cummings, 2005). For the purposes of this study, a non-assimilative MED-HYCOM simulation has also been executed. Atmospheric forcing Navy products are available to us from NRL: NOGAPS (1 and 1/2 degree) and COAMPS (up to 1/5 degree). Higher resolution products (currently 1/10 degree, evolving to 1/20 degree) are available through collaboration with the Hellenic Center for Marine Research (POSEIDON atmospheric model, http://www.poseidon.hcmr.gr, which is based on SKIRON/ETA forcing, http://forecast.uoa.gr/, but with assimilation of real-time data and on-line coupling of coarse and fine domains, see Papadopoulos et al., 2002). Different parameterizations of the Dardanelles outflow have been examined: (i) as a river (near surface discharge); (ii) as a two-layer system of inflow-outflow with transport and mass characteristics prescribed from historical data; (iii) through coupling to a straits model (collaboration with Cheryl-Ann Blain, NRL-SSC).

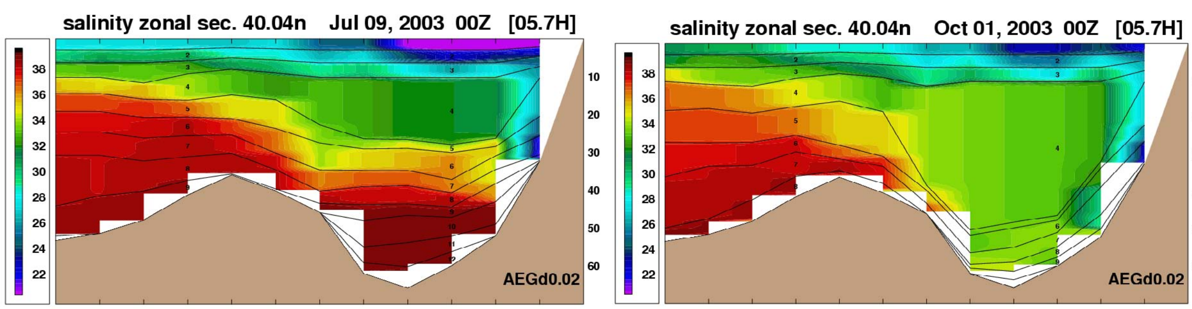

Fig. 2: Snapshots of salinity within the Dardanelles "notch" (marked in Fig. 1) depicting estuarine circulation with high salinity waters of Mediterranean origin near bottom and low salinity waters of Black Sea origin near top. Left: high outflow conditions (summer); right: low outflow conditions (fall).

WORK COMPLETED

Two types of simulations have taken place: process oriented (idealized and/or climatological forcing) and realistic (high frequency forcing). The process oriented simulations have focused on the dynamics of the buoyant discharge and the interaction between the strait and the main topographic features near the discharge site that modify the initial plume evolution. As the HYCOM model has not been previously documented in studies of coastal buoyant discharges, a dedicated study took place that involves new parameterizations of river plume dynamics in HYCOM (Schiller and Kourafalou, 2009). In particular, the role of "estuarine circulation" prior to the discharge of the buoyant outflow was examined and potential vorticity arguments were employed to discuss the changes in outflow properties caused by the sloping bottom (as compared to flat bottom) on the receiving basin. Additional process oriented studies focused on the development and evolution of the Dardanelles plume over the North Aegean basin. The influence of the complex topography was examined through experiments that ranged from fully realistic topography to the artificial removal of deep basins, straits and islands.

The realistic forcing experiments have covered the period 2002-2008; the 2009 simulation is under way. The 2002 simulation was carried out with boundary conditions from a different simulation of the MED-HYCOM as the operational mode started in 2003. Covering the 2002-2003 simulation period allows the employment of drifter data (Olson et al., 2007) for model evaluation through the comparison to model computed synthetic drifters. The 2008-2009 simulation will allow the employment of new data from ancillary projects. The NAS-HYCOM Dardanelles outflow is controlled by a Dardanelles Strait "notch" that has been applied upstream within an idealized representation of the Strait topography and allows the development of a dominantly 2-layer estuarine circulation (Fig. 2). The properties of the outflow in the Aegean are in accordance with seasonal variability extracted from historical data (Kourafalou and Barbopoulos, 2003). Twin experiments with two atmospheric data sets have been carried out: NOGAPS ($1/2^{o}$ resolution) and POSEIDON/SKIRON ($1/10^{o}$ resolution). The latter has allowed a model inter-comparison with a simulation of the NAS-POM model (based on the Princeton Ocean Model, Kourafalou and Tsiaras, 2007). In particular, dense water formation in the NAS-HYCOM (where the deep sub-basins are in the isopycnal coordinate system) and in the NAS-POM (sigma-only everywhere) will be evaluated.

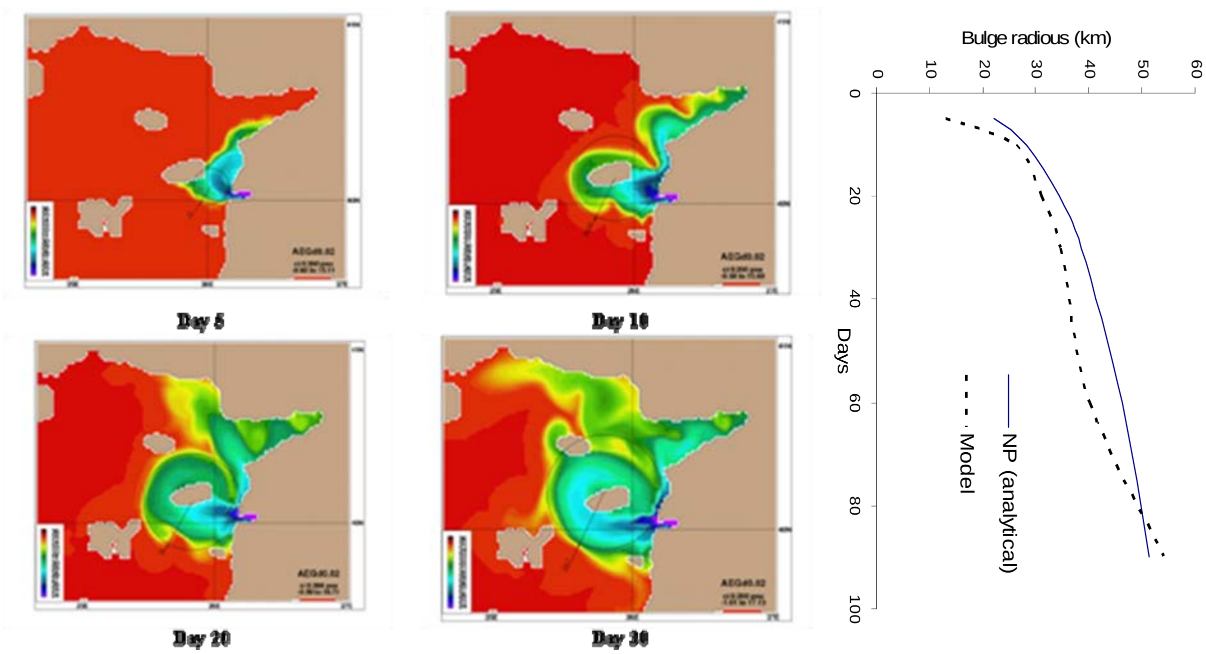

Fig. 3: Left: SSS depicting the development of the Dardanelles plume under buoyancy forcing only (realistic topography). Right: comparison of the bulge radius computed by the model (dashed) and the Nof and Pichevin (2001) analytical solution.

RESULTS

The dynamics of large-scale river plumes were investigated in idealized numerical experiments using the HYCOM model and examining the role of lateral and vertical spreading of the buoyant discharge within the estuary, the impact of different mixing schemes, the role of mass flux (in addition to salt flux) in the plume dynamics and the role of topography in the development and evolution of the buoyant plume (Schiller and Kourafalou, 2009). Tin the presence of buoyant discharge as the only

external forcing, the outflow properties at the river mouth (where observed profiles may be available) greatly impacted the fate of the river plume. In flat bottom conditions, larger mixing at the freshwater source enhanced the estuarine gravitational circulation, promoting larger upward entrainment and stronger outflow velocities. Although the overall geostrophic balance was maintained, estuarine mixing led to an asymmetry of the currents across the strait mouth and to a sharp anticyclonic veering within the estuary, resulting in reduced upstream flow and enhanced downstream buoyancy-driven coastal current. These patterns were altered when the plumes evolved in the presence of a bottom slope. The anticyclonic veering of the buoyant outflow was suppressed, the offshore intrusion decreased and the recirculating bulge was displaced upstream. The sloping bottom impacts were accompanied by enhanced transport and downstream extent of the coastal current. No major changes in the general properties and especially the vertical structure of the plumes were observed when the vertical coordinates were changed from cartesian–isopycnal, to sigma or to sigma–isopycnal. The findings suggest that HYCOM can adequately represent plume dynamics in the North Aegean (or any coastal setting) simulations with realistic topography and forcing, where transitions of the vertical coordinate system are dictated by the prevailing dynamics.

The specific dynamics of the Dardanelles anticyclonic bulge were examined in targeted idealized experiments that sought comparison of model results to large scale outflows, as in Nof and Pichevin (2001). The number of outflow cells, the outflow rate and the morphology of the channel (notch) were found to affect the BSW plume outflow and the propagation outside the Dardanelles mouth. Different simulations were employed regarding the width, the angle, the bathymetry of the channel (notch), the number and disposition of the input cells and the rate of the outflow. Non-dimensional numbers (gradient Richardson number, Froude number, inlet Rossby number and inlet Kelvin number) were calculated for the upper layer's flow at the area of the Dardanelle's mouth. The relation of these numbers with the offshore and coastal extension of the BSW anticyclonic bulge (Fig. 3, left) was also examined for each idealized simulation employing an analytical calculation of the bulge's ballooning as described by Nof and Pichevin (2001), see example in Fig. 3 (right).

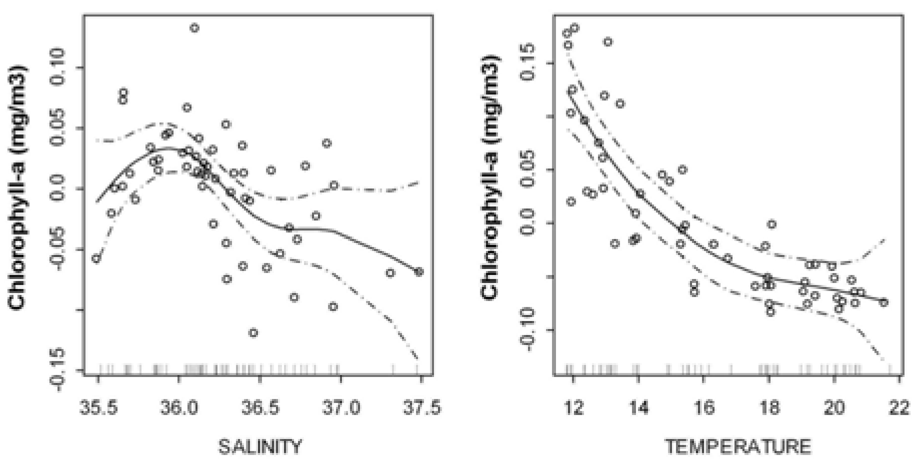

Fig. 4: Results from Generalized Additive Models (GAMs) analysis for a sub-domain in the immediate vicinity of the Dardanelles plume (reaching Limnos island, Fig. 1). The circles are the raw data, the solid line is the main correlation between observed chl-a and model computed SSS (left) and SST (right). The dashed lines give the boundaries of the 95% confidence level.

The realistic experiments (Kourafalou et al., 2009) established the importance of the BSW outflow in the North Aegean dynamics and the implications on the ecosystem dynamics, as well as shelf break processes such as the cascading of dense waters toward the South Aegean, where they can presumably influence the long term variability of deep Eastern Mediterranean water masses (Zervakis et al., 2000). Comparisons of model synthetic drifters to data derived ones from the ONR funded 2002-2003 Aegean drifter experiment (Olson et al., 2007) showed that uncertainties in high frequency variability of the Dardanelles outflow greatly impacted predictions for drifters starting near the Dardanelles Strait. The distinct characteristics of the Dardanelles plume area were also revealed through an interdisciplinary analysis approach (Kourafalou et al., 2008). The North Aegean model domain was divided into sub-regions according to the influence of lateral sources of low salinity, highly productive waters (Dardanelles and rivers); “open sea” areas away from such influences were also defined. SeWiFS data (weekly composites, analyzed with an algorithm specifically developed for the Aegean) were provided through the ancillary SESAME project. Relationships between the remotely observed chlorophyll-a distributions and the hydrodynamic parameters (SST, SSS, SSH and Mixed Layer Depth, MLD) were derived by employing the Generalised Additive Models (GAMs), a flexible regression technique whose advantage over traditional regression methods, such as General Linear Models, is its ability to model nonlinearities using nonparametric smoothers (Raitsos et al., 2009). An example is given in Fig. 4, where the area averaged chl-a distribution in the sub-domain in the immediate vicinity of the Dardanelles outflow (all parameters are time averaged over a year) is highly correlated with low salinity, cool waters (typical properties of the BSW outflow). Interestingly, the salinity value where the correlation is highest varies from year to year, according to the prevailing mixing conditions induced by the atmospheric forcing. While temperature and salinity explain a high percentage of the chl-a variability near the Dardanelles, the MLD has a stronger correlation with the observed chl-a distribution in Aegean open sea waters, indicating a deep source of nutrients there. The model captivated the seasonal variability of water mass characteristics of remote Aegean sub-basins (Kontoyiannis et al., 2002). An important study finding is that differences among water masses in the deep sub-basins appear to be influenced by the degree of proximity to BSW influence. As seen in Fig. 5, the Skyros basin which is generally isolated from direct BSW influence maintains substantially higher salinity in its deepest part. The low salinity near surface waters are especially evident in the Limnos transect, while the Chios transect depicts upper layer low salinity waters of BSW origin in the western side and high salinity waters of Levantine origin in the eastern side. The counter-influence of BSW in the pre-conditioning of these basins for dense water formation during winter cold air outbreaks will be examined in the next year.

IMPACT/APPLICATIONS

This study will set the basis for evaluating improvements in the predictability skill of Aegean Sea and Mediterranean Sea models, by developing and evaluating, for the first time, a parameterization of the outflow of waters of Black Sea origin through the Dardanelles Strait based on observed time series of outflow properties. Analysis of numerical simulations and process oriented experiments on the resulting buoyant plume will advance the knowledge on the dynamics that control (a) the exchange of two basins through straits and (b) the transport rates and pathways of the buoyant waters under the influence of high frequency / high resolution atmospheric forcing and in the presence of complex topography. This study will also provide the Aegean Sea model component of a fully coupled Aegean Sea - Turkish Strait System - Black Sea modeling system, which will serve as a Navy prototype for similar areas of island archipelagos and marginal seas connected by straits. The coupling of the high resolution North Aegean HYCOM model with an unstructured grid model of the TSS has already taken place (Blain et al., 2009). The upcoming use of data to evaluate the coupled system will be a

valuable benchmark for the modeling of coupled coastal and wetlands models that are critical for optimizing Navy missions. The seasonal and inter-annual variability of the plume controlled salinity distributions will also serve as the basis for the study of biophysical implications, related to the contribution of the eutrophic Black Sea waters on water clarity and productivity of the Northern Aegean Sea.

RELATED PROJECTS

This study is the ONR funded component of an international effort; the extensive collaboration allows considerable leveraging and data sharing.The University of Miami (UM/RSMAS), the Naval Research Lab (SSC and MRY) and the NATO Undersea Research Center (NURC) have been working closely together to establish the scientific objectives and the collaboration logistics to improve the understanding of inter-basin exchanges through straits. The study area chosen for the development of a comprehensive project that will serve as a baseline for the related scientific objectives is the Turkish Straits System (TSS) and the outflows (Northern Aegean Sea and Western Black Sea). The NURC R/V Alliance completed two data campaigns in August-September 2008 and January-February 2009 (head of the NURC/TSS08 mission: S. Besiktepe). NRL-SSC (PIs E. Jarosz and B. Teague) deployed moored instruments in the TSS (including in the Dardanelles Strait). In addition, we collaborated in the planning of CTD casts and drifter releases within the Dardanelles plume. A total of twelve drifters were released in sets of three instruments at four different locations. The drifters were provided by NURC and by an ancillary ONRG-NICOP funded project for a TSS drifter study (PI P.M. Poulain). A unique data set is expected, which will be availbale to us and provide updated estimates of the Dardanelles outflow. PI Kourafalou participated in a joint meeting at NURC (Oct. 1-2, 2009) to discuss preliminary results of data analysis. In addition, an ancillary project at NRL-SSC (PI C.A. Blain) will utilize these measurements to calibrate the high resolution, unstructured grid model of the TSS and provide boundary conditions to the NAS-HYCOM model developed in this project; the coupling of the two models has already taken place (Blain et al., 2009).

An ancillary European project has been funded by the EU (Integrated Project SESAME: http://www.sesame-ip.eu/); the lead Institute is the Hellenic Center for Marine Research (HCMR). PI Kourafalou is an external collaborator of HCMR; leveraged EU funds include Ph.D. student and post-doc support. In addition, data available to us at no cost to ONR include new hydrographic data in the vicinity of the Dardanelles outflow and re-analysis of SeaWiFS imagery for the entire Aegean Sea. PI Kourafalou also collaborated with HCMR in data analysis on the buoyancy-driven flows in the western Black Sea (main source of BSW) to improve the understanding of the variability of the BSW pathways through the Turkish Straits System.

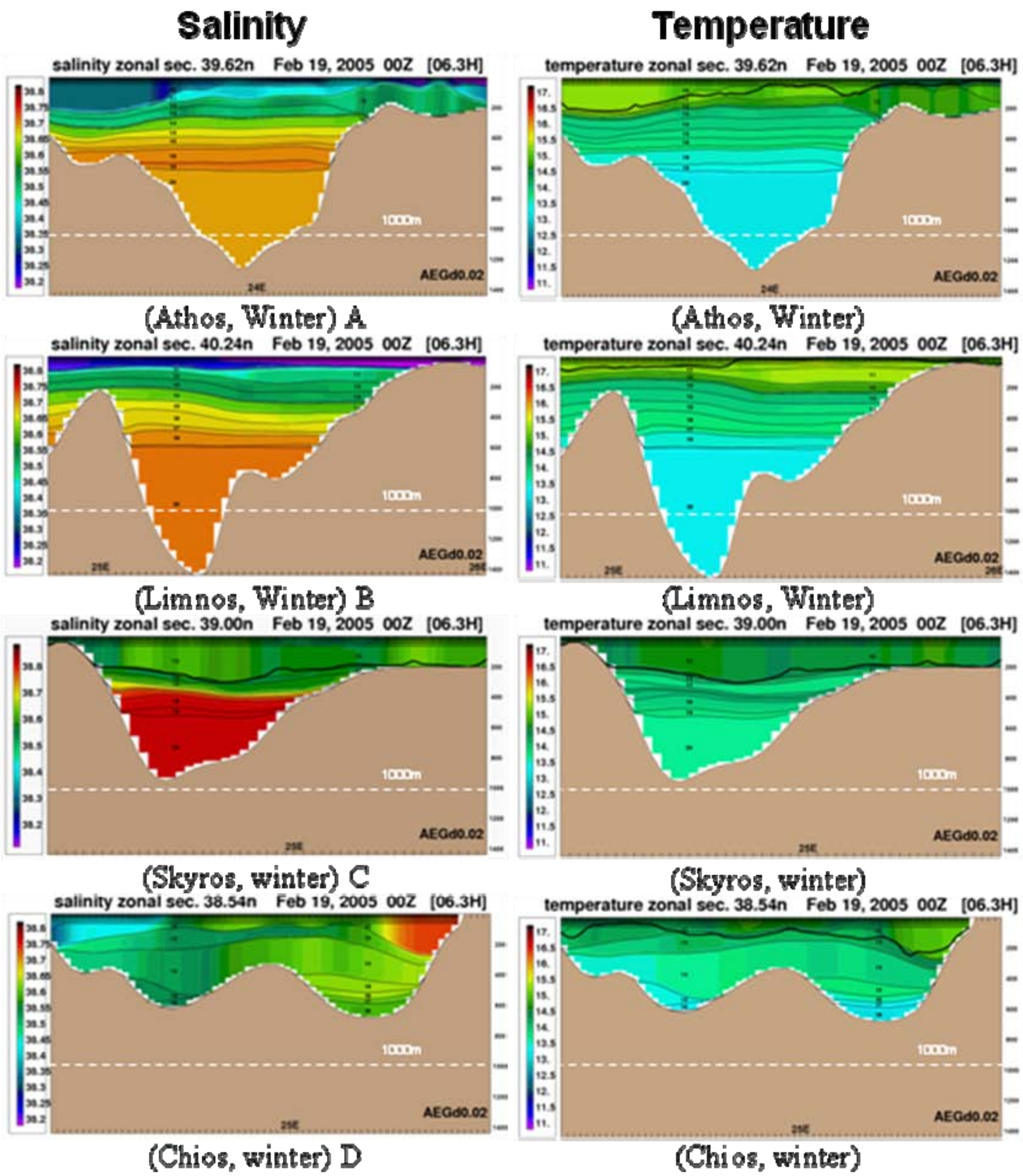

Fig. 5: Sections of model computed salinity (left) and temperature (right) across the North Aegean deep basins marked in Fig. 1; examples are for the winter of 2005.The dashed white line markes the 1000m depth.

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